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Palaeoenvironment of a Late Quaternary lacustrine–palustrine carbonate complex: Zarand Basin, Saveh, central Iran

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Abstract

The continental carbonate deposits of the Zarand Basin were deposited within an intra-continental strike-slip basin situated in the northwestern corner of central Iran. They consist of distal alluvial mudstones to marlstones, carbonate pond deposits, carbonate and siliciclastic-infilled channels, and lacustrine carbonates deposited within a distal alluvial–lacustrine–palustrine complex. Both sedimentological and palaeontological evidence suggest that these sediments mostly formed within an open hydrological system. The common presence of root traces, greyish green mudstones, calcareous nodulisation, mottling, and desiccation breccias indicate a palustrine setting. The carbonate deposits of the Zarand Basin were formed under an overall semi-arid climate but periods of more aridity characterised by extensive calcretization can be distinguished in the stratigraphical sections. Both tectonics and climate have contributed in controlling the sedimentation of the Zarand Basin. Archaeological and geomorphological evidence provides a unique sub-recent analogue for ancient palustrine limestones developed within an intra-continental basin under a semi-arid climatic regime. The combination of geological and archaeological data and their comparison with historical documents show that the so-called historical lake of Saveh was the remnant of the more ancient wetland system which dominated the Zarand region during the late Quaternary.

Keywords: Lacustrine carbonate; Distal alluvial mudstone; Palustrine; Late Quaternary; Zarand Basin

1. Introduction

The shallow setting of many carbonate lakes results in the frequent sub-aerial exposure of marginal lacustrine areas during the lake-level low-stands. Sub-aerially exposed lacustrine carbonates undergo more or less intensive pedogenic alteration which produces the palustrine limestones characterised by a range of sedi-

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mentary and pedogenic features including root traces, pseudo-microkarsts, mottling, desiccation breccias, and calcareous nodules (Freytet, 1973; Freytet and Plaziat, 1982; Freytet, 1984; Platt and Wright, 1992; Alonso-Zarza et al., 1992b). Palustrine carbonates are closely associated with calcretes and sometimes the distinction between the main features of these two types of carbonates is really difficult to recognise. Fluctuations of the water table are responsible for creating this difficulty (Alonso-Zarza, 2003). Palustrine limestones are interpreted as the pedogenic products of three main continental settings: (a) low-gradient marginal lacustrine environments (Freytet and Plaziat, 1982; Freytet, 1984; Platt, 1989), (b) extensive, very shallow carbonate marshes (Plaziat, 1984; Platt and Wright, 1992; Wright and Platt, 1995), and (c) ephemeral lakes and ponds developed on floodplain environments of alluvial systems (Gierlowski-Kordesch et al., 1991; Alonso-Zarza et al., 1992a,b; Sanz et al., 1995; Gierlowski-Kordesch, 1998; Tanner, 2000).

The Florida Everglades which is a complex mosaic of shallow freshwater carbonate environments in the southeastern United States is the most famous and well-studied modern analogue for ancient palustrine sequences (Platt and Wright, 1992). However, the limited thickness of carbonate deposits, their formation under a sub-humid climate and under marine influence, and the lack of close association with alluvial systems (Platt and Wright, 1992) are the disadvantages of the Florida Everglades as a modern analogue for palustrine sequences developed under semi-arid climatic regimes. The sequences described from Spain, especially at Las Tablas de Daimiel, appear as a good modern analogue for freshwater palustrine environments developed under semi-arid climates (Alonso-Zarza, 2003). The nature and development of palustrine sequences are closely related to the climatic conditions and some characteristic facies models have been proposed for palustrine sequences developed under different climatic regimes (Platt and Wright, 1992). Palustrine carbonate deposits are also a valuable tool to infer some tectonic pulses, to reconstruct aggradation–accommodation relationships in alluvial systems, and to provide a sedimentary archive for measuring $p\mathrm{CO_2}$ and photosynthetic pathways in terrestrial plants in association with calcretes (Alonso-Zarza, 2003).

The carbonate deposits of Zarand were detected after the discovery, in historical and archaeological documents, of a former lake in central Iran called Saveh Lake (Djamali, 2002; Okhravi and Djamali, 2003). These deposits display a wide range of lacustrine, palustrine and alluvial facies representing an ancient lake. Human activities seem to be the main cause for the complete desiccation of this ancient lake system, demonstrating the high sensitivities of such ecosystems to anthropogenic influence (Okhravi and Djamali, 2003).

The aims of this contribution are: (1) to describe the depositional environment and palaeoecology of carbonate facies of a late Quaternary lacustrine–palustrine complex in the Zarand Basin, central Iran; (2) to deduce the overall palaeoclimatic condition of the region in central Iran during the late Quaternary for which no previous data are available; (3) to show that the carbonate facies are a unique sub-recent analogue for palustrine facies, and (4) to investigate the relationship between the missing historical Lake of Saveh and the final stage of the evolution of the ancient Zarand wetland system.

2. Physical setting

2.1. Geographical and geological setting

The study area occurs within the Zarand Plain, a semi-arid region with a mean annual precipitation of about 210 mm, located some 80 km SW of Tehran and 35 km N of the town of Saveh (Fig. 1). The studied carbonates of the Zarand Plain have been deposited in the Neogene extensional fault-bounded Zarand basin. This inter-mountainous basin is located at the north-western edge of the structural zone of central Iran (Stocklin, 1968). A preliminary analysis of the distribution of fault systems on satellite image (Fig. 2C), along with the geometrical, rhombohedral shape of the basin, strongly suggests a strike-slip origin that appears to be related to a local extension between two major fault systems in the north and south of the basin (E. Shabanian, pers. comm.).

The basement and surrounding mountains are composed of Eocene volcanics and volcaniclastics which represent the major sediment source for the basin alluvial systems. The Oligo-Miocene marine limestones (Qum Formation), Mio-Pliocene continental siliciclastic rocks (URF: Upper Red Formation), and Pliocene conglomerate units are also exposed in the area (Fig. 1). Apart from the Quaternary alluvial and colluvial sediments in marginal areas, the continental carbonate deposits of Zarand represent the topmost basin-filling stratigraphical unit of the region. No previous study has been devoted to these continental deposits. Caillat et al. (1978), dealing with the general geology of the Saveh region, did not differentiate the carbonate deposits of the Zarand basin. Because the lithology and erosional

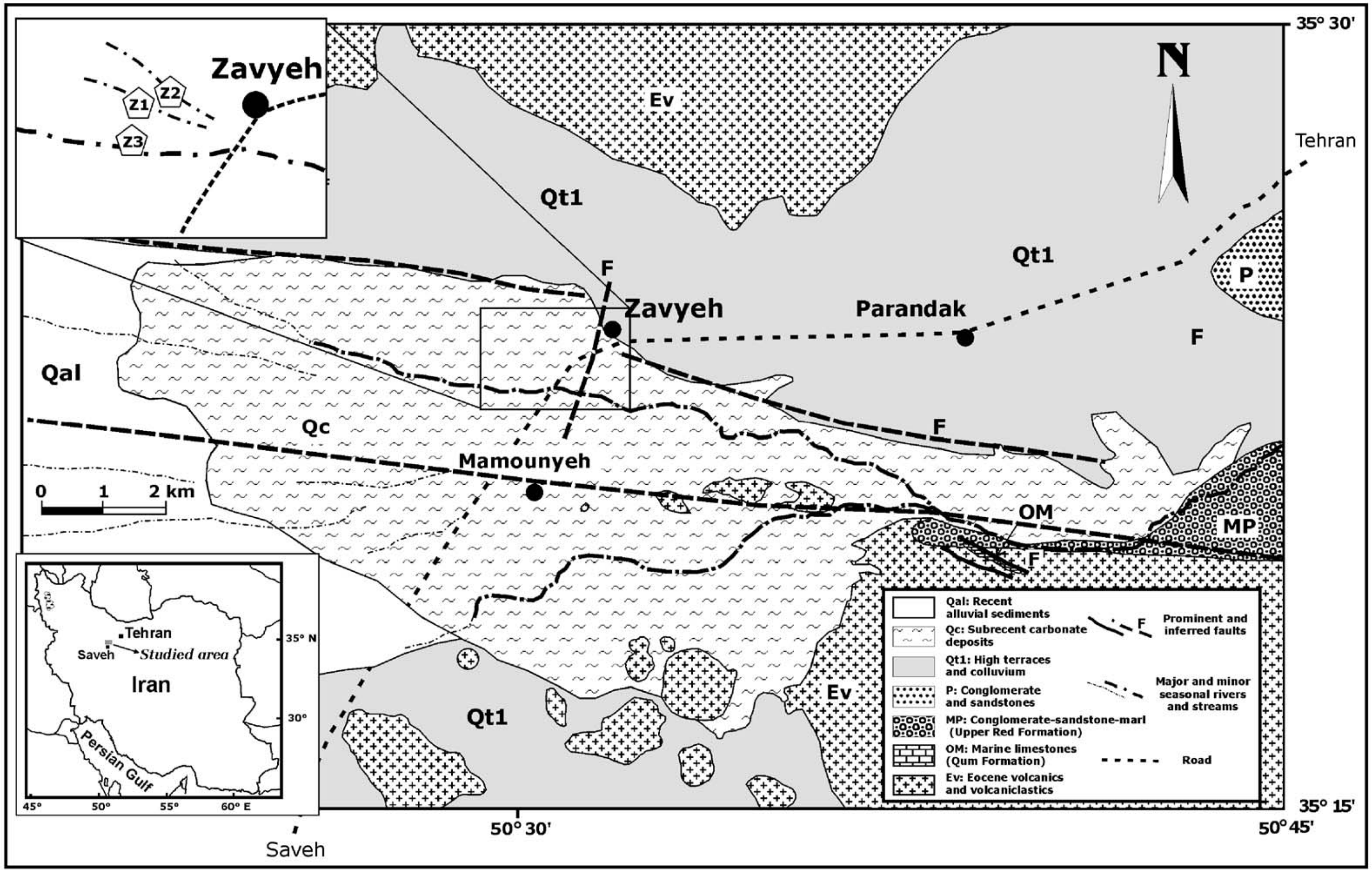


Fig. 1. Geological map of the Zarand Basin. Inset (upper left) shows the location of the sedimentological logs.

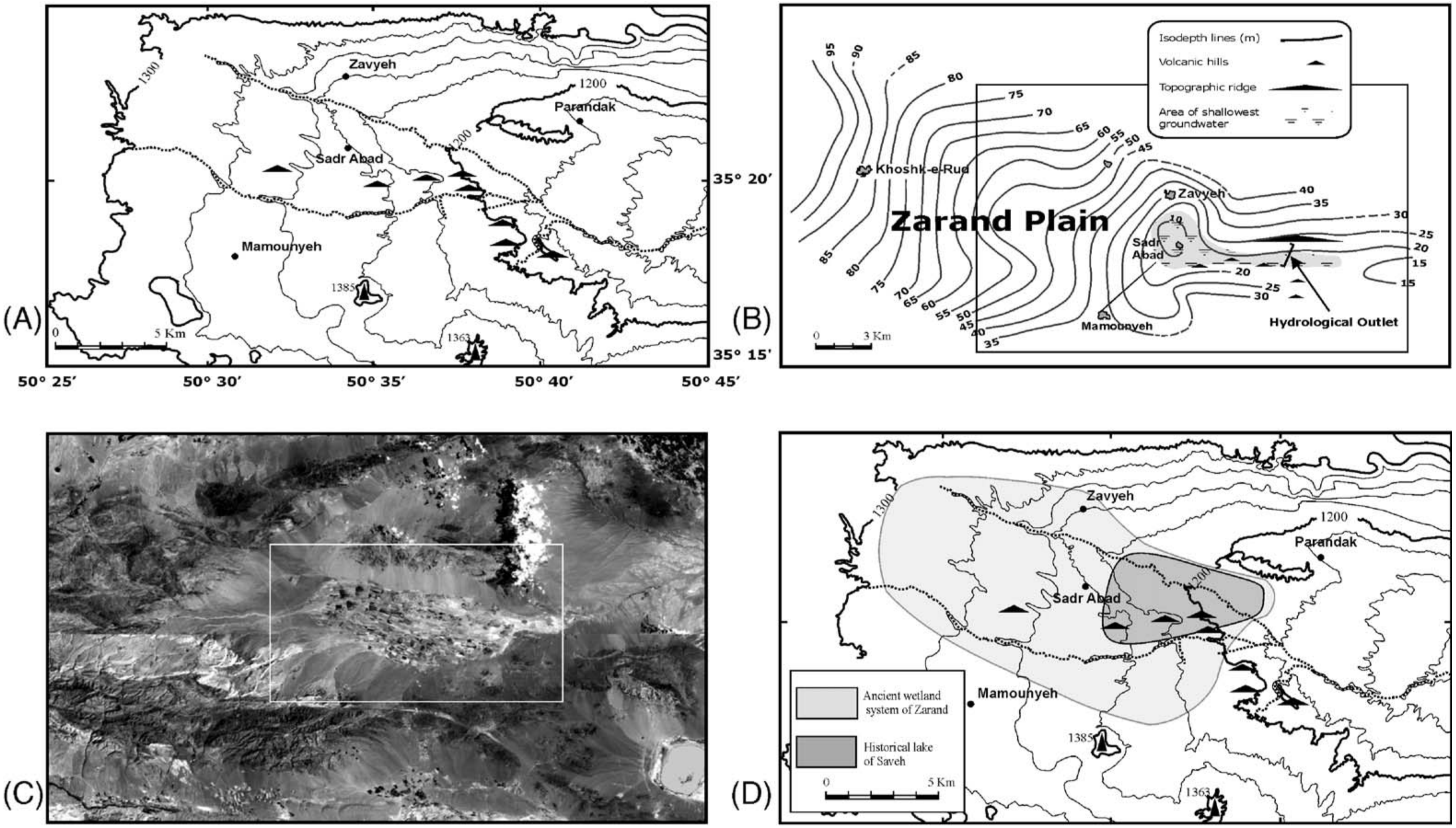


Fig. 2. Aerial extent of ancient lake of Zarand (Saveh Lake). (A) Topographical map of the Zarand plain shows a very gentle slope towards the east and a narrow outlet between the volcanic hills and the high ridge SW of Parandak. (B) The present-day groundwater table is closest to the surface around Sadr Abad (Hydrogeological Report on Zarand Plain, 1992) and in the eastern part of the basin indicating the high potential of this zone to produce a wetland system with a rise in the level of the water table. (C) Aerial extent of Zarand carbonate deposits as observed in the satellite image follows the areas of highest water table level. (D) The contraction of the ancient Zarand wetland system to the eastern part of the basin.

features of these carbonate deposits highly resemble those of the mudstone members of the URF, the Quaternary carbonate deposits were identified incorrectly as the Mio-Pliocene URF (Nogol Sadat et al., 1984).

2.2. Hydrology and topography

Fig. 2 shows the topographical and hydrogeological maps as well as the satellite image of the Zarand Basin. The Zarand basin is a bowl-shaped depression with a hydrologic outlet situated in the extreme eastern limit of the Zarand plain, near Parandak. The plain itself gently slopes towards the east and the whole drainage system of the basin discharges via the narrow outlet in the east between a set of volcanic hills to the south and a topographical ridge to the north (Fig. 2A and B). The water table approaches the plain surface eastwards from 95 m depth in the western section of the Zarand plain up to 10 m depth near Sadr Abad (Fig. 2B). Comparison of the topographical and hydrogeological contours demonstrates that the eastern parts of the Zarand basin can be a potential site for the formation of a wetland system. This area is exactly the place in which the studied carbonate deposits are concentrated (Figs. 1, 2C), and is the most probable site for the ancient Lake of Saveh, a historical lake that is said to have disappeared a few thousand years ago (Fig. 2D).

2.3. Age estimate and the historical lake of Saveh

Due to lack of datable material, it is very difficult to evaluate the temporal framework in which the studied carbonates were deposited. However, the dispersed stone tools of Neolithic age over hill tops (to the W of Zavyeh) point to the beginning of the Holocene as the upper limit (Okhravi and Djamali, 2003). Thus, the studied sedimentary profiles, which are concentrated on a higher topographical terrace to the W of Zavyeh, seem to be of late Pleistocene age (Fig. 1).

An important problem arises when studying the archaeological data and historical documents and comparing them to the present geomorphology of the Zarand Basin. Historical documents show the presence of a lake or marsh environment in the Zarand region during historical times, most probably between 1000 and 5000 years ago (Djamali, 2002; Okhravi and Djamali, 2003). The geomorphological observations as well as topographical and hydrogeological data indicate that the east-central part of the basin has subsided due to a neotectonic activity. The wetland system of Zarand, formerly covering a large area in the centre of the basin, is now shifted to the east-central portion of the basin. This contracted wetland system, or lake referred to as Saveh Lake in historical documents, covered the area until a few thousand years ago. Anthropogenic activities in the form of groundwater acquisition in Qanat systems and even land reclamation appear to have promoted the disappearance of the historical lake of Saveh (Okhravi and Djamali, 2003). Qanat systems were invented and utilised for the first time by the native people on the Iranian Plateau about 2800 BP. (Goblot, 1979). The present high water table in the east-central Zarand basin demonstrates the high potential of the area for the formation of a wetland system through even a small rise of the water table (Fig. 2B).

In summary, the evolution of the Zarand wetland system is marked by two different stages separated by a neotectonic event, which caused the subsidence of the east-central part of the basin. Consequently, the wetland shifted to the eastern part of the basin where it survived until historical times (Fig. 2D). The focus of the present study is on the sedimentary profiles situated in the west of Zavyeh to which a late Pleistocene age is assigned.

3. Materials and methods

The study area presents many outcrops along the sides of gully that consist predominantly of one facies, i.e. grey and brown mudstones with carbonate nodules (see below) which exceed rarely 2 m of thickness and show no distinctive feature to make their correlation possible. Nevertheless, there are two small valleys in the west of Zavyeh showing good outcrops from which the sedimentary logs (Z1, Z2, and Z3) were measured (Fig. 1). The location of the sedimentary log Z3 was selected in order to be the best representative of the whole facies succession along the geological transect (Fig. 3). Logs Z1 and Z2 were measured from two isolated small outcrops in a gully located 200 m to the north of Z3 (Fig. 1). Some representative samples were thin-sectioned and their carbonate contents were measured using the loss-on-ignition method (Dean, 1974). Colors were described using the Munsell Color Chart.

Sampling for calcareous fossils was carried out in the sandy limestones (*LC*, see below for facies description). Molluscs, ostracods, and charophyte gyrogonites were recovered from five samples by washing and sieving. In sedimentary log Z3 (Fig. 3), from base to top, they correspond to: the basal limestone lens or charophytic sandy limestone (*LC*) including samples MDZB13 (at 4.65 m), MDZB13″ (at 4.80 m), MDZF1 (at 6.30 m), and MDZF2 (at 6.85 m). In sedimentary log Z2 (Fig. 1), one sample was taken

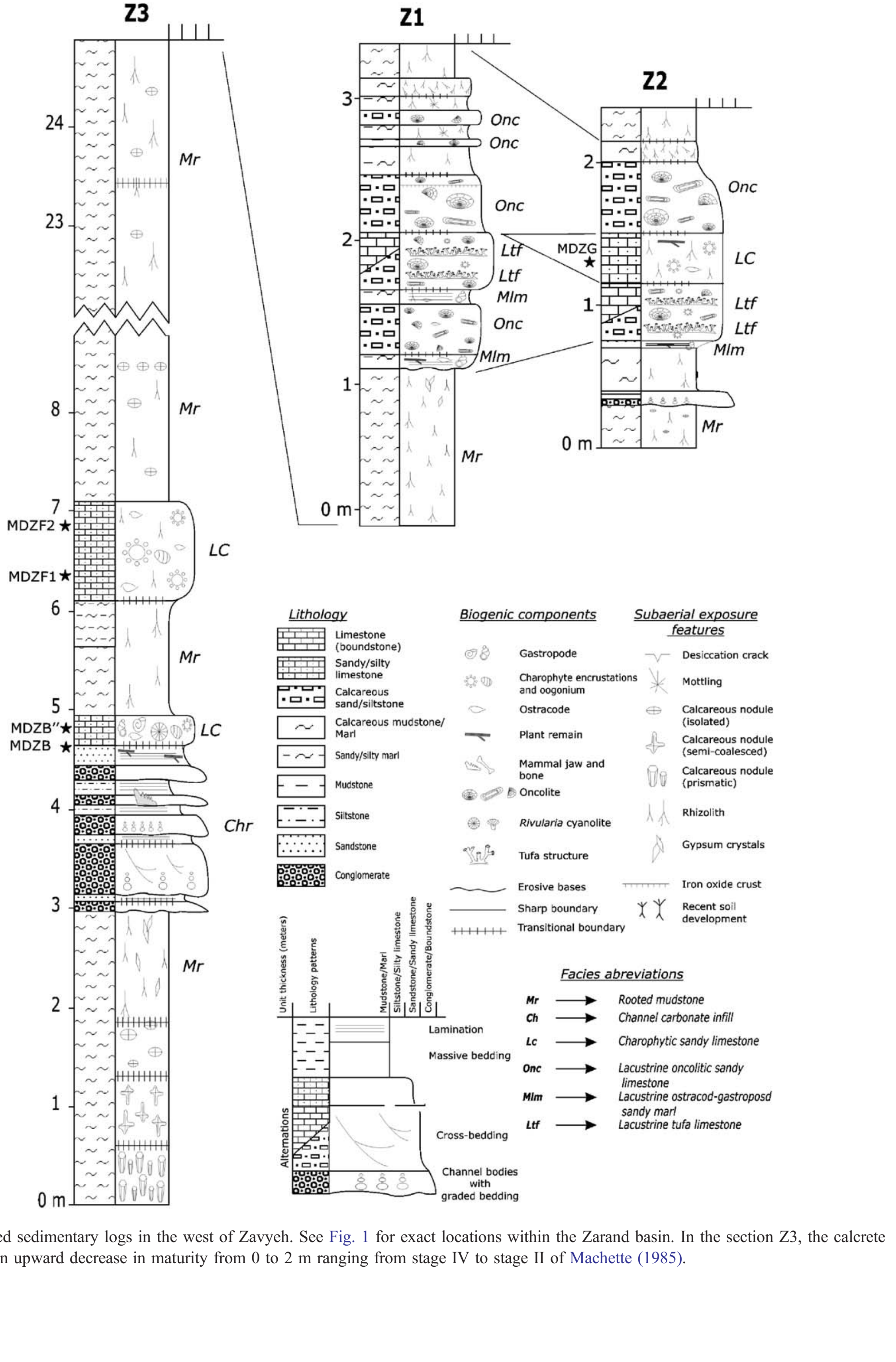


Fig. 3. Measured sedimentary logs in the west of Zavyeh. See Fig. 1 for exact locations within the Zarand basin. In the section Z3, the calcrete profiles show an upward decrease in maturity from 0 to 2 m ranging from stage IV to stage II of Machette (1985).

from the *LC* facies [sample MDZG (at 1.30 m)]. The fossils were isolated from the 125 μm sieved fraction and transferred onto microslides for further identification. Charophyte gyrogonites from three very rich samples were measured with a Leitz-binocular equipped with a micrometre. Photographs were taken with a Jeol 6300F electron microscope to investigate morphological details. Molluscs were picked out under a binocular microscope and then identified.

4. Results

4.1. Sedimentology

Lacustrine and palustrine carbonate facies in Zarand plain interfinger with the alluvial fan deposits that extend from the bordering elevations along the basin margins (Fig. 4A). The carbonates show a wide range of facies which represent five different sedimentary facies associations: coloured massive rooted mudstones (*Mr*), lenticular rudstones (*Chr*), conglomerates and sandstones (*Chc*), charophytic sandy limestones (*LC*), and oncolitic sands-laminated silty marls-tufa limestones (*Onc-Mlm-Ltf*) facies associations.

4.1.1. Coloured massive rooted mudstones to marlstones (Mr)

This facies association is composed of greyish green and reddish brown rooted mudstones to marlstones (*Mr*) with many carbonate nodules. In the Munsell Color Chart for soil colours, the greyish green mudstones are commonly 5Y 7/2, 5Y 7/1, 5Y 8/2 and 5Y 8/1 and the reddish brown mudstones fall in the 10YR 5/3, 10YR 6/2 and 10YR 6/3 categories. Although much of the mudstones appear massive, the alternation of the different-coloured pseudo-layers creates a bedding-form appearance at a metre-scale (Fig. 4B). The thickness of this unit ranges from one to more than 15 m. The presence of root casts with root channels filled by a mixture of iron oxide and clay minerals is a characteristic feature (Fig. 4C). In some horizons the root channel infills are partly or completely replaced by gypsum crystals. Mottling is not common and when present appears relatively pale. Rarely, in some horizons, a brecciated fabric can be discerned in which the millimetre-sized angular mud clasts of different colours are embedded within a muddy groundmass.

The calcium carbonate content of an unaltered greyish green mudstone averages 21 wt.% and can increase to 83% for the pedogenic horizons with highest concentrations of $CaCO_3$.

4.1.2. Calcrete profiles

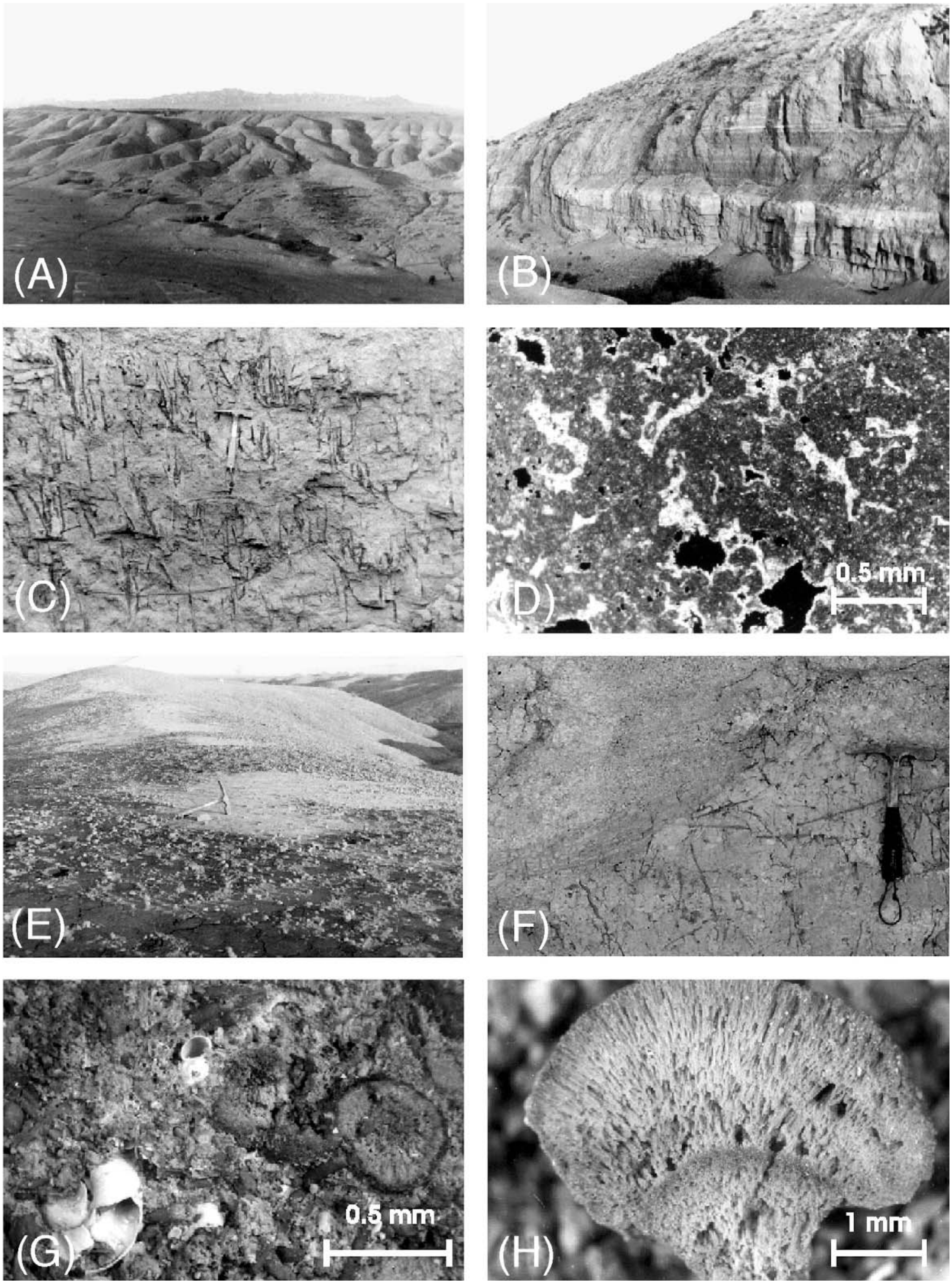
The mudstones of the coloured massive rooted facies (*Mr*) contain many calcareous nodules and calcrete horizons. The isolated nodules range in shape from nearly spherical to very irregularly globular to vertically elongated and their size varies from a few millimetres up to 10 cm. They are well indurated and have sharp boundaries with the encompassing muddy matrix and are not associated with mottling. When included in the green and grey mudstones, the boundaries are more diffuse. Microscopic observations show a micritic matrix with floating etched quartz and feldspar sand- and silt-sized grains. Within some nodules, curved and circumgranular cracks and a peloidal fabric are well represented (Fig. 4D). In this granular fabric of the nodules, calcite cementation is partly developed and sparry calcite fills some voids completely and forms isopachous rims around peloids or as linings. This fabric is not discernible in the encompassing rooted grey and brown mudstones.

The erosion of marly matrix between carbonate nodules concentrates them on the ground creating a lag-like deposit particularly on the tops of hills (Fig. 4E). The isolated nodules may coalesce and in some horizons these coalescing nodules form very hard and thick layers with a columnar or prismatic structure equivalent to the Stages II to IV of the morphological classification of calcretes (Gile et al., 1966; Machette, 1985). Stage II calcretes consist of isolated calcareous nodules in a non-calcareous to slightly calcareous matrix concentrated in discrete horizons with gradational tops and bases. Stage III comprises the semi-coalesced nodules which in more mature states create a prismatic structure and Stage IV profiles are composed of very compacted platy–laminar horizons (Machette, 1985; Tanner, 2000). The calcrete profiles are well represented in the sedimentary log Z3 where they display an upward gradual change from the stage IV at the base, to isolated nodules of stage II in the upper parts (from 0 to 2 m of the section in Fig. 3).

4.1.3. Lenticular rudstones (Chr), conglomerates and sandstones (Chc)

In the Zarand carbonate deposits, a range of lenticular conglomeratic bodies are found with matrix varying from almost pure carbonate to the mixed siliciclastic–carbonate sands and silts. The clasts can as well be carbonate and/or siliciclastic. Two end-members can be clearly distinguished which are more or less concentrated in distinct clusters in the studied profiles. Here, these two bodies are referred to as rudstones (*Chr*) which are carbonate-dominated and conglomerates and sandstones (*Chc*) which are siliciclastic-dominated.

The rudstones (*Chr*) are composed of pebble to large size clasts mainly composed of carbonate. Phytoclasts, thin organic rich bands, carbonized macrophytic debris,



and in rare cases, ostracods and gastropods, are found in association. The matrix is mainly composed of carbonate. Trough cross-bedding and graded bedding are the most conspicuous internal structures of this facies. The rudstones form mostly small lenses of 10 cm thickness and 1 m width on average. The well-rounded pebble-sized clasts are micritic in composition.

In siliciclastic conglomerates and sandstones (*Chc*), which contain a major proportion of siliciclastic materials, the lenticular bodies may be up to 1.5 m in thickness and more than 10 m in lateral extent. The average size of the pebbles is about 0.5–1.5 cm in diameter grading upward into laminated coarse- to medium-grained sandstones which are composed of quartz grains, feldspars, volcanic lithics, and mud clasts cemented with calcite. Trough cross-bedding and graded bedding are the typical sedimentary structures.

The contact of the carbonate lenticular bodies with underlying mudstones or other units is erosional whereas their upper contact is planar and transitional with the overlying organic-rich horizons or mudstones or may be cut by later similar bodies (Fig. 4F). Laterally, they may be amalgamated or be located adjacent to a topographical high or to small lenticular biogenic limestone. It is at the top of two of these bodies (*Chr*) that vertebrate bone fragments and rodent jaws were discovered (log. Z3, Fig. 3).

4.1.4. Charophytic sandy limestones (LC)

These are packstone facies consisting of ostracod, gastropod and charophyte remains and cyanophytic algal balls exhibiting intensive calcification. At the outcrop scale, these units form lenses extending laterally from a few metres to more than 100 m, their thickness varying from a few decimetres up to 2 m (Fig. 5A).

This facies is composed of charophyte stem encrustations and gyrogonites, ostracods, gastropods, millimetre- to centimetre-sized algal balls and algal encrustations, especially around the numerous macrophyte stems (Fig. 4G, H). All these facies components are in direct contact with each other and cemented by a poorly developed micritic matrix but the facies as a whole is soft to moderately lithified (Fig. 5B). Charophyte stem encrustations and gyrogonites are commonly intact showing original morphological features. The ostracods and gastropods are also unbroken and intact. Nearly all these biogenic components are encrusted with a thin layer of micrite.

Only rare siliciclastic grains are present. Calcite cement is rarely present within inter- and intra-particle porosity. The most interesting sedimentological feature of this facies is the presence of many algal balls and encrustations with radially arranged calcite microtubes (Fig. 4G, H). The carbonate content of this facies, determined by loss on ignition, is from 61 to over 68 wt.% and carbonate composition is low magnesian calcite with a 0.7 to 1.8 mol.% of $MgCO_3$.

The contact with the underlying green rooted mudstones to marlstones (*Mr*) is mostly sharp while the upper contact with the same lithology is more transitional. The gentle palaeo-topographical variations at the time of deposition are discernible at the base of the units (Fig. 5A). Desiccation breccia and root traces are absent and a crude layering can be distinguished. In sedimentary log Z3 (Fig. 3), the lower charophytic unit (4.65–4.95 cm, the location of samples MDZB13 and MDZB13″) is darker and contains gastropods and algal balls in comparison to the upper charophytic units which are white in colour and characterised by the dominance of charophyte and ostracods and lack of gastropods and algal balls.

4.1.5. Oncolitic sands–laminated silty marls–tufa limestones (Onc–Mlm–Ltf)

This facies association is traceable over hundreds of metres. It has an average thickness of 1.5 m and appears to have filled ancient topographical lows. The lower contact with underlying gypsiferous green mudstones is very sharp while the top of the unit gradually changes into a mottled mudstone and then to a relatively hardened green mudstone with many fine root traces. This facies association is represented by the alternation of three facies comprising an oncolitic sandy facies, a gastropod–ostracodal laminated silty marl, and a tufa limestone. These units, described in detail below, present a total thickness of up to 2 m.

Fig. 4. (A) General view of the natural outcrops of the Zarand carbonate deposits 2 km to the west of Zavyeh. (B) The ledge–forming white coloured bed near the base of the section Z3 is the charophytic sandy limestone (*LC*). (C) Root channels in the green/brown mudstones (basal part of the log Z3, Fig. 3). (D) Thin section displaying a disrupted micrite texture within calcareous nodules of distal alluvial mudstones (*Mr*), highly resembling the circumgranular cracks of palustrine limestones. Sample was taken from the 1.5 m level of section Z3 (Fig. 3). (E) Lag deposit composed of calcareous nodules liberated after the erosion of the marly matrix covering a hilltop. See the hammer as the scale, at the centre of the picture (30 cm long). (F) The juxtaposition of rooted mudstones (right) and carbonate channel infill (left). The photo is taken from the basal part of log Z3, Fig. 3. (G) Photograph illustrating the main sediment components of charophytic sandy limestone (*LC*, log Z3; sample MDZB13″) containing gastropod and algal balls (*LC*). Gastropod fragments, algal balls and charophyte stem encrustations are shown. (H) Magnified image showing a *Rivularia* calcite skeleton with the radial calcite tubes (facies *LC*, log Z3).

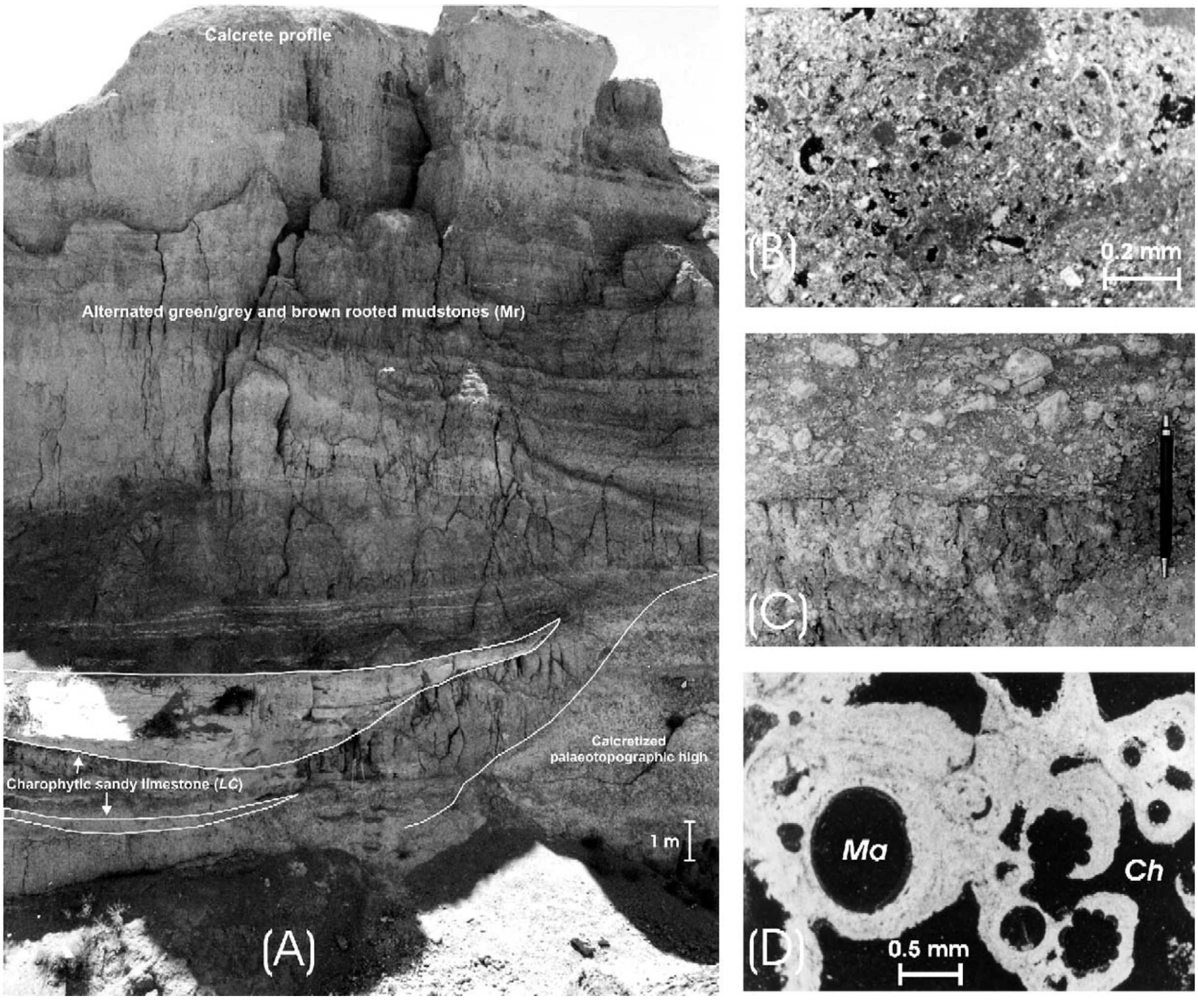


Fig. 5. Facies relationships and thin sections of the Zarand lacustrine deposits studied in the southwest of Zavyeh. (A) Photograph showing the lateral and vertical facies relationships at the side of a valley SW of Zavyeh. The lenticular white layer near the base of the photo is a charophytic limestone lens (*LC*) embedded within the mudstones to marlstones of facies *Mr*. The photo was taken from the location of section Z3 (Fig. 3). Note the role of palaeo-topography in controlling the sedimentation pattern. (B) Thin section of the charophytic sandy limestone facies (*LC*) showing the near absence of calcite cement and the prevailing micritic particles formed after the degradation of charophyte encrustations. Thin section was prepared from sample MDZF1 taken from 6.3 m of section Z3 (Fig. 3). (C) Sharp contact between lacustrine oncolitic limestone with underlying green rooted mudstones. Photo was taken from a small outcrop located between sections Z1 and Z2 (Fig. 1). Note the rhizoliths and spherical oncolites floating in a calcareous sandy matrix. (D) Cross-section of encrusted charophyte stems (*Ch*) and macrophytic rhizoliths (*Ma*) from the tufa limestone facies (*Ltf*, log Z2, Fig. 3). The length of the pen in the photo is about 15 cm.

4.1.5.1. Oncolitic sands (Onc). This facies occurs as layers with a mean thickness of 30 cm alternating with tufa limestone layers and fossilferous laminated silty marls. The oncolitic sandy facies is composed of carbonate and siliciclastic sands containing many sand to pebble-sized spherical and subspherical oncolites and cylindrical macrophyte stem encrustations or rhizoliths (Robbins et al., 1991), sometimes as long as half a metre (Fig. 5C). Some small rhizoliths became the nuclei for later oncolites, which range in size from a few millimetres up to 7 cm. The oncolites show both radial and concentric internal fabrics and may be well lithified or very spongy with the irregular outer surfaces. In the field, oncolites look very much like the calcareous nodules of pedogenic origin, but the lower density of the oncolite and their cauliflower appearance make them more distinctive.

4.1.5.2. Gastropod–ostracodal laminated silty marl (Mlm). This sediment is dark grey calcareous silty marl containing only disseminated charophyte remains, ostracods, algal fragments and a few gastropods. This facies is not lithified and shows a millimetre-scale lamination with an average thickness of 20 to 30 cm.

4.1.5.3. Tufa limestone (Ltf). This is a boundstone forming a reef-like structure composed of abundant calcite tubes fused together with calcite cement (Fig. 5D). The tubes vary in diameter (from <1 mm up to a few millimetres) and length (from a few millimetres up to a few centimetres) and may be filled or remain empty. They are perpendicular to the bedding plane and their diameter widens upwards to the top of each bed. The thickness varies from 5 to 15 cm. In fact, there is a transition from the gastropod/ostracodal laminated silty marl (*Mlm*) with dispersed charophyte stems at the base of this facies. This facies unit is very well lithified in comparison to the facies *Mlm* and *Onc*. It is completely composed of low magnesian calcite with 0.65 mol.% $CaCO_3$.

4.2. Palaeontological analyses

The species composition of the samples collected from section Z1, 2 and 3, is reported in Table 1.

4.2.1. Molluscs

Mollusc remains are represented by several well preserved specimens of aquatic gastropods, generally slightly encrusted by calcium carbonate, occurring in the *LC* facies (Fig. 4G). They are abundant only in one sample (MDZB13″). The recorded mollusc assemblage shows a strictly oligotypic character being composed of only two species: *Pseudamnicola* cf. *raddei* Böttger, a Prosobranch of the family Hydrobiidae, and *Gyraulus laevis* (Alder), a Pulmonate of the family Planorbidae. *P.* cf. *raddei* dominates the assemblage with a percentage of 75%. *P.* cf. *raddei* is very close to *P. raddei*, known from Turkmenistan (Zhadin, 1952). The ecology of this species is poorly known. However, most of the representatives of genus *Pseudamnicola* prefer to live in springs and their overflows and spring-fed water-bodies (Zhadin, 1952), on rocky and sandy substrata, often among the bank stream vegetation (Giusti and Pezzoli, 1980).

G. laevis is probably a Holarctic species, found throughout Europe, parts of North Africa, and in western Asia (Meier-Brook, 1983; Kerney, 1999) where it is recorded also in Quaternary deposits (Zhadin, 1952). Its ecological requirements are clean, quiet, and hard or soft shallow lacustrine waters or pond environments rich in aquatic macrovegetation, but it can also live in slow-flowing water. This species can tolerate slightly brackish water (Zhadin, 1952; Økland, 1990; Kerney, 1999). The recorded mollusc assemblage from the Zarand basin thus points to a fresh, shallow water-body with slow-flowing waters possibly also fed by springs. Moreover the oligotypic character of the mollusc assemblage can be indicative of cool water and of a very shallow or ephemeral water body. Similar oligotypic conditions are very well documented by non-marine molluscs from European Quaternary lacustrine successions (Lobek, 1964; Esu and Girotti, 2000).

4.2.2. Ostracods

Ostracods were analysed from the sieved fraction at 125 μm from five samples coming from *LC* facies. All samples were rich in ostracods and the valves were well

Table 1
Fossil content of the major carbonate lacustrine and pond deposits (facies *LC* in sections Z2 and Z3)

Sample no.	Facies	Ostracods	Gastropods	Charophytes
MDZB13	Charophytic sandy limestones (*LC*)	•*Ilyocypris gibba* •*Candona* (N.) *neglecta* •*Trajancypris* sp. (only juveniles)	–	*Chara vulgaris*
MDZB13″		•*Ilyocypris gibba* •*Candona* (N.) *neglecta* •*Psychrodromus* sp. (only juveniles) •*Trajancypris* sp. (only juveniles)	•*Gyraulus* (family Planorbidae) •*Pseudamnicola* (family Hydrobiidae)	*Chara vulgaris*
MDZF1		•*Cyprideis torosa* •*Ilyocypris gibba* •*Candona* (N.) *neglecta* •*Trajancypris* sp. (only juveniles)	–	*Chara vulgaris*
MDZF2		•*Cyprideis torosa* •*Heterocypris salina* •*Ilyocypris gibba* •*Candona* (N.) *neglecta* •*Trajancypris* sp. (only juveniles)	–	*Chara vulgaris*
MDZG		•*Ilyocypris gibba* •*Cyprideis torosa*		

See stars for stratigraphic locations in Fig. 3.

preserved. The most common species were represented by adults and instars (population structure type B, Whatley, 1988), thus, they can be considered in situ remains and reliable for palaeoenvironmental investigations.

On the whole, six taxa have been recognised: *Candona neglecta* Sars, *Ilyocypris gibba* Ramdohr, *Heterocypris salina* (Brady), *Cyprideis torosa* (Jones), *Psychrodromus* sp. and *Trajancypris* sp. (juv.). All these species are living and well known, and show a wide geographical distribution (Meisch, 2000), including the Iranian region (Hartmann, 1964). Janz et al. (2001) recorded their presence also in the Holocene sediments of Varzaneh (Isfahan–Sirjan basin, central Iran).

Samples MDZB13 and MDZB13″, coming from the lower *LC* lens (log Z3, Fig. 3), included the dominant *C. neglecta* and *I. gibba*, accompanied by rare valves of *Psychrodromus* sp., while only rare juvenile valves of *Trajancypris* sp. were collected. This association points to a fresh, stagnant or slow-current, shallow water-body.

Samples MDZF1 and MDZF2, coming from the upper *LC* lens (log Z3, Fig. 3), were composed of dominantly *C. torosa*, accompanied by abundant *C. neglecta*, *I. gibba*, and *H. salina*; rare juveniles of *Trajancypris* sp. were also recovered. The presence of the dominant *C. torosa*, which is a typical brackish water dweller, together with *H. salina*, suggests that, at this moment, the waterbody was ion-enriched. This assemblage requires slightly saline water, up to 5.5‰ for *I. gibba* (Neale, 1988), and dominated by Na^+ and Cl^- (*C. torosa* and *H. salina*), even if they can be also of athalassic origin (Van Harten, 1990; Gliozzi and Mazzini, 1998).

Sample MDZG, coming from the *LC* facies (log Z2, Fig. 3), included an oligotypic assemblage, composed dominantly of *I. gibba* and rare *C. torosa*, pointing to the slow restoration of a freshwater domain.

4.2.3. Charophytes

Charophytes are a new tool of lacustrine biomarkers, especially valuable for arid and semi-arid regions (Soulié-Märsche, 1991; Garcia, 1994). Significant results were obtained for Holocene palaeolakes in North Africa (Gasse et al., 1987; Kröpelin and Soulié-Märsche, 1991). Their study can provide complementary information about salinity, depth and temperature of former water bodies (Fan et al., 1996; Soulié-Märsche, 1998). Charophyte gyrogonites were present in five samples, along with the ostracods in the *LC* lenses (sections Z2 and Z3, Fig. 3) (Table 1).

One hundred gyrogonites of the three most abundant samples were measured for statistical analyses and comparison. The gyrogonites from the five samples are very similar and belong to one species. The average size was about 510 μm in height and 390 μm in width and an average H/W ratio of 1.32 (Table 2). The morphology and the measurements of the gyrogonites compared most closely to *Chara vulgaris* Linnaeus, a modern species, well known from European localities (Soulié-Märsche, 1989) (Fig. 6). The gyrogonites of this taxon were previously described in detail based on extant populations from the Mediterranean region and Morocco (Soulié-Märsche, 1989). Very similar fructifications were shown to occur also in the Holocene sediments from North Africa (Soulié-Märsche, 1993; Zalat, 1996). The distribution of *C. vulgaris* is worldwide. Charophytes were poorly studied in Iran, however living *C. vulgaris* was mentioned from four localities during botanical investigations carried out in 1972 in central and southern Iran (Compère, 1981, p. 36). The species is also known from several localities in India (Pal et al., 1962).

C. vulgaris is an ubiquitous species adapted to many kinds of environments. Usually it thrives in shallow fresh- to low saline water where it produces abundant gyrogonites. The salinity tolerance of *C. vulgaris*, up to 0.75 g per mil (Zaneveld, 1940; Corillion, 1957), is markedly lower than that for *C. torosa*. The Zarand basin charophytes most likely correspond to very shallow temporary freshwater ponds or small lakes. The coexistence of both gyrogonites and plant fragments can be considered a sign of in situ fossilisation of a former charophyte meadow.

The presence of only one species of charophytes, limited to the opportunistic *C. vulgaris*, clearly indi-

Table 2
Chara vulgaris L. — biometrical values for gyrogonites from three different levels of the Zarand basin sections (see stars for stratigraphical locations in Fig. 3 logs)

Sample *n*	Min	Mean	Max
Height (μm)			
MDZF2	400	<495>	570
MDZF1	440	<516>	600
MDZB13″	420	<528>	610
Width (μm)			
MDZF2	320	<384>	450
MDZF1	320	<394>	450
MDZB13″	340	<390>	480
H/W ratio			
MDZF2	1.07	<1.29>	1.63
MDZF1	1.10	<1.31>	1.62
MDZB13″	1.08	<1.36>	1.69

Number of measurements is 100 for each sample.

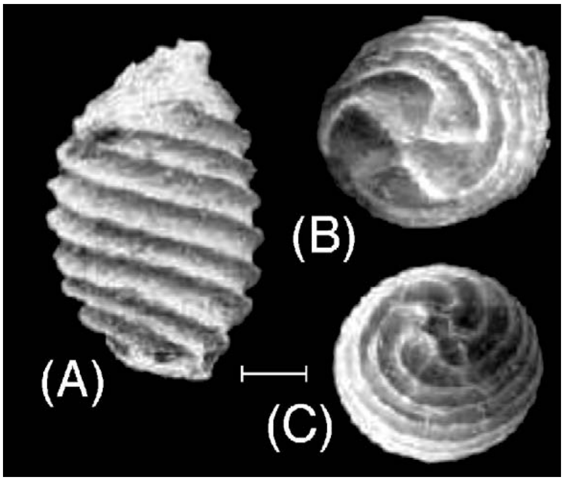


Fig. 6. *Chara vulgaris* L. — gyrogonites from sample MDZB13 (section Z3, see log in Fig. 3). (A) lateral view; (B) apical view; (C) basal view. Scale bar is 100 μ.

cates that the salinity of the ponds had always remained very low. Indeed, if the salinity had increased to meso-polyhaline conditions, the flora should be composed of the halotolerant *Lamprothamnium papulosum* (Wallr.) J. Groves, a typical indicator for sabkha-like environments (Soulié-Märsche, 1998).

5. Interpretation and discussion

A summary of the palaeoenvironmental interpretation of all facies and facies associations is presented in Table 3 including both sedimentological and palaeontological evidence.

5.1. Depositional environments of the Zarand carbonates

The calcium carbonate required to form the huge carbonate deposits of Zarand was obviously provided by erosion of calcareous rocks of the catchment area. Indeed, the limestones of the Oligo-Miocene Qum Formation and also the marly members of the Qum and the Mio-Pliocene Upper Red Formations that crop out in the surrounding elevations represent the most important source of calcium carbonate for the Zarand carbonate deposits.

5.1.1. Floodplains and mudflats of distal alluvial environments: coloured massive rooted mudstones (Mr) and calcrete profiles

The overall characteristics of the *Mr* facies indicate its deposition in a distal alluvial setting where the sedimentation took place in floodplains of fluvial systems and/or in distal mudflat environments associated with alluvial fans. A similar fine-grained facies constitutes the dominating facies of many lacustrine–palustrine settings (Alonso-Zarza et al., 1992a,b; Sanz et al., 1995; Tanner, 2000).

The common presence of root traces shows an exposure required for the development of vegetation. These periods coincide with the times of groundwater lowering and lake-level low-stand, when plant roots penetrated several decimetres downward in search of water (Fig. 4C). On the other hand, the dominant grey colour, which is common for palustrine carbonates (Platt and Wright, 1992), demonstrates a hydromorphic condition suggesting relatively long periods of high water level. The periods of complete desiccation are deduced from the presence of desiccation breccia in some discontinuous horizons. Brown rooted mudstones seem to have formed under a more oxidising condition with more prolonged stages of low water table compared to the greenish grey mudstones. Preliminary maceration of the green and grey rooted mudstones has yielded a substantial amount of pollen grains indicating that the sub-aerial exposure episodes were quite short compared to waterlogged periods favouring good preservation of pollen and spores. The disrupted micrite fabric in the calcareous nodules which is still an in-

Table 3
Summary of the palaeoenvironmental analysis of the Zarand basin carbonates

Facies association	Facies	Palaeoenvironment
Coloured massive rooted mudstones (*Mr*)	Coloured massive rooted mudstones (*Mr*)	Floodplain areas and distal alluvial flats
Lenticular rudstones, conglomerates and sandstones (*Chr* and *Chc*)	Rudstones/sandstones (*Chr*) Mixed carbonate–siliciclastic conglomerates/sandstones (*Chc*)	Mixed carbonate–siliciclastic alluvial plain
Charophytic limestones (*LC*)	Charophytic limestones (*LC*)	Carbonate small lake/pond: shallow low-energy freshwater to slightly brackish (oligohaline) domain
Oncolitic sands–laminated silty marls–tufa limestones	Oncolitic sands (*Onc*) Tufa limestones (*Ltf*) Laminated silty marls (*Mlm*)	Shallow freshwater lacustrine environments

complete form of a well-defined granular fabric may have formed through the process called "grainification" (Alonso-Zarza et al., 1992b). An alternation of dry and wet conditions is a prerequisite for the development of this texture probably resulting from considerable water table fluctuation (Wright, 1990b).

Secondary gypsum crystals as a late post-depositional phenomenon are a common feature on many former floodplains (Gierlowski-Kordesch et al., 1991). In the case of the Zarand deposits, they probably penetrated and precipitated in root channels from concentrated surface waters saturated in calcium sulphate that transiently covered the floodplain depressions.

Calcrete profiles have largely developed within the mudstones of distal alluvial environments. They seem to be mostly of pedogenic rather than of groundwater origin as evidenced by the rarity of mottling, relatively sharp boundaries of the calcareous nodules with surrounding muddy matrix, and the transitional nature of the upper boundary of massive calcrete units with the overlying marlstones (Alonso-Zarza, 2003). Moreover, no profiles can commonly be distinguished in most cases in groundwater calcretes (Alonso-Zarza, 2003) whereas the calcrete stages can easily be distinguished in Zarand (log Z3, Fig. 3). The vertically elongated nodules provide another evidence of the pedogenic origin of calcrete horizons especially in the lower part of the sedimentary log Z3 (Fig. 3).

5.1.2. Carbonate channel environments: lenticular rudstones, conglomerates and sandstones (Chr and Chc)

The lenticular geometry, internal primary sedimentary structures, nature of the upper and lower contacts, well rounded sands and gravels, and lateral relationships with adjacent units suggest deposition in fluvial channels. The carbonate-dominated nature of many channel infills or rudstones (*Chr*) reflects channels located in the middle of a depositional setting dominated by carbonate sedimentation. This can be inferred by comparison with Mesozoic analogues described earlier from the Iberian Range (Gierlowski-Kordesch et al., 1991) and from the Miocene of the Teruel Graben, Spain (Alonso-Zarza and Calvo, 2000). Calcareous pebbles and sand/silt-sized micrite grains are the evidence of this clastic carbonate setting. Carbonate pebbles are mostly micritic and structureless, resembling pedogenic calcareous nodules. These reworked calcretic nodules are clearly one of the most important transported elements within these palaeo-channels. The channel fills composed of reworked calcrete deposits have recently been reported from Permian and Triassic red alluvial sediments of Minorca (Gómez-Gras and Alonso-Zarza, 2003) and from the Lower Cretaceous (Weald) of the Iberian Range in Spain (Gierlowski-Kordesch et al., 1991). The varying proportion of extraformational siliciclastic and intraformational carbonate pebbles within the Zarand channel fills is another sedimentary aspect similar to that of the channel fills from Minorca and the Iberian Range (east-central Spain). The channel and interchannel environments (facies *Chr*) contain fossil remains of vertebrates. The flowing waters were probably fresh with well-developed vegetation in the area as evidenced by common carbonized macrophytic fragments and rhizoliths.

Gómez-Gras and Alonso-Zarza (2003) report three types of carbonate channel fill in the Permian and Triassic of Minorca, Spain. Type 1 includes the small lenticular bodies filling the small scour surfaces. These are interpreted as ephemeral channels and sheet-floods on the interfluvial channel systems which removed only immature calcretes (Stage I–III) after heavy rain. The run-off originated from within the alluvial plain. Type 2 comprises sandstone 3-D bodies formed by floodwaters flowing down the levees of major streams. Type 3 represents channel–floor lag deposits of the major streams that drained a large part of the alluvial plain. These channels contain both intraformational reworked calcretes and siliciclastic grains of extrabasinal origin.

In Zarand, the majority of the studied carbonate channel fills are the equivalents of Type 1 reworked calcretes (*Chr*). This indicates that they are the result of the local erosion and short-distant reworking of calcrete nodules developed in floodplain areas and distal alluvial flats. The larger mixed carbonate–siliciclastic channel infills (*Chc*) which are specially clustered in the eastern section of the studied valley in west of Zavyeh are equivalent to Type 3 channel fills of Minorca. This means that they formed in channels receiving the sediment supply and water, partly from the extra-basinal highland areas and partly from the intra-basin drainage system.

5.1.3. Carbonate pond and/or small lake environments: charophytic sandy limestones (LC)

The bioindicators associated with this facies suggest very shallow, fresh- to slightly brackish water domains for the deposition of facies *LC*, inferring lake/pond sedimentation. Based on the fossil assemblages, the palaeoecological conditions appear to have been very similar for the two fossiliferous layers located, respectively, at 4.65–4.955 and 6.1–7 m. However, some differences can be deduced from the specific composition.

This facies is a biogenic carbonate deposited in a shallow small lake/pond environment within a topographical depression probably located on the floodplain or an interchannel area (Fig. 5A). The presence of algal balls (lower *LC* lens, Fig. 3) and advanced calcification features denote shallow and clear water condition with very small waves or currents in marginal areas favouring the formation of many semi-spherical algal structures (Fig. 4H). Gastropods and ostracods are well preserved indicating that the wave currents were not so intensive and that there was a zone of macrophytes surrounding the ecosystem. This is confirmed by the presence of many plant remains, located especially in the basal part of the lower lens of section log Z3 and the *LC* unit of section Z2 (Fig. 3). The evidence for the low energy condition is also provided by the unbroken charophyte stem encrustations and gyrogonites and by the lack of oncolites and oolites despite the strong calcification processes that dominated the environment.

Internal fabric of the algal balls or cyanoliths (sensu Riding, 1983) is very similar to the calcitic skeletons produced by the cyanobacterium *Rivularia haematites* with radially arranged calcite tubes formed around the sheaths of the trichoms of the cyanophyte (Schneider, 1977). This species and probably other cyanophyte species have also played an important role in the calcification and bioerosion processes in sediment components of this facies. The low magnesian calcite mineralogy of the bulk samples, with a Mg/Ca ratio less than 2, corresponds well to this type of lake/pond water (Müller et al., 1972).

In the lower lens (4.65–4.95 m, Fig. 3), the presence of *C. neglecta* and *I. gibba* among ostracods and the dominance of *Pseudamnicola* among gastropods point to slow currents. The abundance of macrophyte remains and the occurrence of the gastropod *G. laevis* further indicate the presence of well-developed aquatic vegetation. Thus, the lower lens of the *LC* sandy limestone facies was probably laid down in a shallow low-energy freshwater domain with slow currents.

In the upper charophytic unit (6.1–7.1 m), the dominance of *C. torosa* and the presence of *H. salina* among ostracods indicate a brackish water environment. However, the presence of both charophyte gyrogonites and stem encrustation refers to at least three months of submersion at low salinity. This is the minimum time span required by the charophytes to fulfil their life cycle and produce the gyrogonites (Soulié-Märsche, 1991). Germination of *C. vulgaris* takes place about four weeks after flood and requires freshwater conditions. The plants can develop up to a threshold of 0.75 g L^{-1} of salinity and then decay. The salt-tolerant ostracods could survive at higher salinity as long as the pond held water. Thus, the upper sandy limestones (6.1–7.1 m) interval can be interpreted as deposited in a shallow, slightly brackish (oligohaline) domain. The concentration of Mg ions in the lake water was very low ($Mg/Ca < 2$) as indicated by the precipitation of low magnesian calcite (Müller et al., 1972).

In summary, the *LC* facies formed under shallow fresh- to brackish water conditions in low topographical depressions or the interchannel environments of distal alluvial environment. The dispersed rare siliciclastic sands/silts incorporated into the *LC* facies reflect flooding phases of the adjacent fluvial channels.

5.1.4. Shallow lacustrine environment: oncolitic sands–laminated silty marls–tufa limestones

These three facies (*Onc*, *Mlm*, and *Ltf*) are interpreted as shallow lacustrine deposits associated with a large belt of macrophytic vegetation. A depositional model for this shallow lacustrine setting, based on the vertical facies succession of the three above-mentioned subfacies, is suggested in Fig. 7. The calcretized zone (log Z1 and Z2, Fig. 3) probably formed near the more or less oscillating position of the groundwater table. The presence of mottling is evidence for the hydromorphic conditions. High evaporation and evapotranspiration seems to be two important processes in the precipitation of carbonate and the formation of this calcretized layer (Semeniuk and Meagher, 1981).

Oncolites formed in areas dominated by wave action and the elongated macrophyte encrustations or rhizoliths (Robbins et al., 1991) indicate the relatively more protected, thickly vegetated areas. The gastropod/ostracod laminated silty marl facies (*Mlm*) corresponds to sedimentation in the central and deepest parts of this lacustrine environment. The abundance of unbroken ostracods, gastropods and gyrogonites, and the well-developed lamination point to their sedimentation under open water conditions.

The tufa structures (*Ltf*) characterise the more shallow zones that received enough sunlight for colonisation by charophytes and other macrophytes. Thin sections taken perpendicularly to the calcite tubes reveal that the tubes are thickly calcified charophyte stem fragments and sometimes other macrophyte stem encrustations (Fig. 5D). The calcite tubes tend to become larger and are more thickly coated with calcite towards the upper layers, suggesting increasing concentration of HCO_3^- in the water.

The *LC* facies is rarely found intercalated within the shallow lacustrine facies association (see section Z2; 1.15–1.5 m, Fig. 3). The oligotypic ostracod assem-

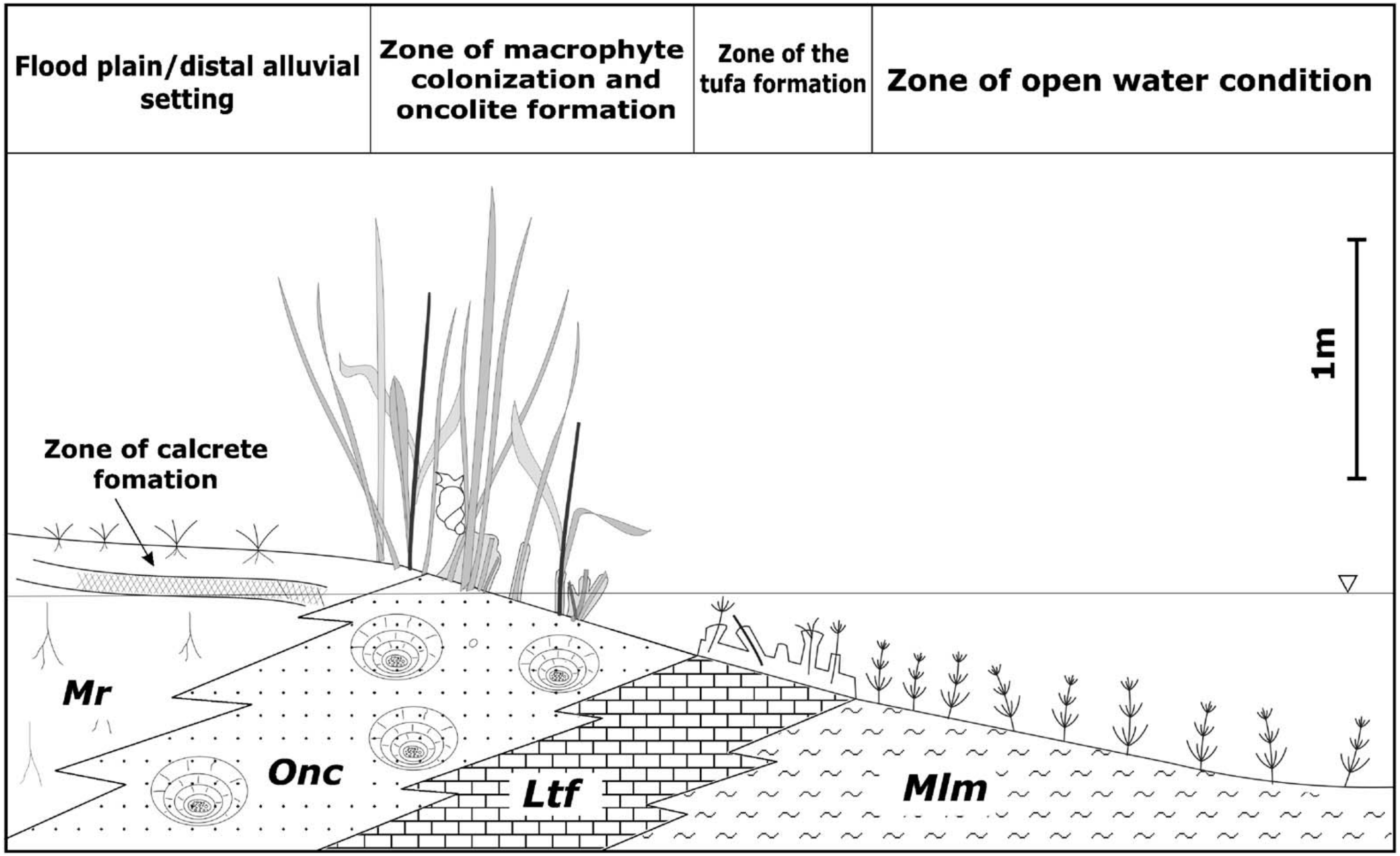


Fig. 7. Simplified model for the lateral succession of the shallow lacustrine limestone facies (facies *Onc* = oncolitic sands, *Ltf* = tufa limestone, and *Mlm* = gastropod–ostracodal laminated silty marl as observed in sections Z1 and Z2).

blage (dominant *I. gibba*, accompanied by *C. torosa*) and the presence of the gyrogonites of *C. vulgaris*, although less abundant than in the previous levels, suggest the restoration of freshwater conditions in a shallow water body for the *LC* facies of section Z2. In addition, the environment was characterised by slow currents as all species of genus *Ilyocypris* are rheophilic. The location of this facies could represent a small embayment or protected shallow area adjacent to the main water body of the lake.

The oncolitic sandy facies (*Onc*) displays some similarities to those formed in large fluvial channels flowing in many palustrine settings such as in the Eocene Guarga Formation, southern Pyrenees, Spain, (Nickel, 1982) and in the Late Cretaceous and Early Tertiary of southern France (Freytet and Plaziat, 1982). Although oncolites may also form from river currents as in the above examples, the geometry of the deposits studied here suggests they formed in lake areas which were exposed to wave action. Indeed, the lateral extension of the oncolitic beds, the presence of rhizoliths, and the lack of sedimentary structures typical for channel environments, such as cross-bedding and graded bedding, suggest a lacustrine littoral environment rather than a fluvial channel environment (Freytet and Plaziat, 1965). Because the facies is completely composed of low magnesian calcite, the Mg/Ca ratio of the water at time of deposition must have been less than 2 (Müller et al., 1972).

6. Environmental synthesis: tectonic or climatic control?

The carbonate deposits of the Zarand Basin are interpreted as sediments deposited in a distal alluvial–lacustrine–palustrine complex formed on a gently-sloping alluvial plain. Both the fossil content and sedimentological evidence show the dominance of fresh-to slightly brackish hard water conditions. Sedimentation took place in carbonate channels with siliciclastic input, floodplains, distal alluvial mudflats, and small hard water lakes and ponds.

This carbonate complex formed mostly under an open hydrology that favoured a relatively stable, near surface groundwater table with minor oscillations of the water level. The presence of palustrine features such as grey and green coloured mudstones with carbonate nodules and root channels, as well as mottling and desiccation breccia are some evidence of this near surface fluctuating water table. In addition, the dominance of freshwater conditions and the lack of evaporite deposits confirm a dominantly open hydrology and therefore the Zarand Basin can not be compared to a "*through-flow playa*" as defined by Rosen (1994). This hydrological context is a prerequisite for the development of palustrine carbonates, as demonstrated in many parts of the world (Freytet and Plaziat, 1982) and particularly in the intracontinental basins of Spain (Alonso-Zarza et al., 1992a,b; Sanz et al., 1995, Alonso-Zarza, 2003).

In the Teruel Graben (Spain), lacustrine–palustrine sedimentation has been controlled by a combination of climate, tectonics, and source rock (Alonso-Zarza and Calvo, 2000; Alonso-Zarza et al., 2000). In the Florida Everglades, topography and more particularly the seasonal climate are the main controlling factors for the lateral distribution of carbonate environments (Platt and Wright, 1992). In contrast, in the Lower Cretaceous (Weald) of the east-central Spain, subsidence and sediment supply and not climate are considered as the most important factors in determining lacustrine and palustrine carbonate sedimentation because climate was stable (Gierlowski-Kordesch et al., 1991).

Sediment+water supply and subsidence are the most important parametres controlling sedimentation which are in turn controlled by climate, tectonics and source rock. These factors determine the lake basin morphology and the nature of basin infills (Alonso-Zarza, 2003; Alonso-Zarza and Calvo, 2000; Bohacs et al., 2000). However, caution should be taken in deciding on the relative importance of either factors in sedimentation of the Zarand complex.

According to Bohacs et al. (2000), climate and tectonics through their control on the sediment+water supply (mostly climatic) and the rate of accommodation change (mostly tectonic), exert coequal influence on the occurrence, distribution and characteristics of lake-basin infills. Comparison of the Zarand facies with the lacustrine facies associations of the lake basin types as proposed by Carroll and Bohacs (1999), tend to classify the Zarand context as a balanced-fill basin. In this lake-basin type, the rates of sediment+water supply and accommodation are roughly in balance during the formation of the sedimentary sequences. However, water inflows are not always in equilibrium with outflows and are occasionally insufficient to fill the accommodation space. This results in the climatically driven lake level or groundwater fluctuations (Bohacs et al., 2000). Hence, in a balanced-fill basin such as Zarand, water table fluctuations can at least partly be attributed to climate oscillations.

The oldest stratigraphical unit of the Quaternary of the Zarand basin consists of well-developed calcrete profiles, well exposed at the base of the valley to the west of Zavyeh (Fig. 3). An overall arid to semi-arid climate can be deduced from this lithology interpreted as palaeosols (Machette, 1985). A decrease in the maturity of these calcrete profiles, can be interpreted in terms of a decrease in intensity and duration of this arid period (Tanner, 2000). Generally, more humid conditions favour the development of palustrine sequences rather than calcretes because they provide enough water to develop carbonate water bodies (Alonso-Zarza, 2003). Hence, the thick basal calcrete profiles of the Zarand have most probably formed under strongly arid conditions. Whether this arid period coincided with the Last Glacial Maximum (about 25,000 to 15,000 years ago), as already documented for western Iran (Van Zeist and Bottema, 1977), still needs more palaeoecological evidence. In addition, a relatively long-term tectonic quiescence may have caused landscape stability and promoted the formation of these calcretes.

For all the younger facies overlying this calcrete basal unit, an overall semi-arid to sub-humid climate is suggested. This inference is made because the carbonate deposits of Zarand display the palustrine features between the semi-arid and intermediate-type palustrine facies sequences as defined by Platt and Wright (1992). Lack of evaporites in this part of the sections and extensive desiccation breccia excludes a totally semi-arid climate. On the other hand, the absence of microkarst features shows climatic conditions less humid than would be required for the intermediate-type palustrine sequences (Platt and Wright, 1992).

Some useful insights can be made about the tectonic control in Zarand basin sedimentation according to the interpretations made for the Miocene of the Teruel Graben (Alonso-Zarza and Calvo, 2000) and the Permian–Triassic of the Minorca (Gómez-Gras and Alonso-Zarza, 2003). The required accommodation space for deposition of the Zarand carbonate deposits has been created by local tectonism. The development of thick distal alluvial mudstones with dispersed nodular calcrete horizons and reworked calcretes has likely resulted from the equilibrium between tectonic subsidence and continuous vertical aggradation in distal alluvial environments. The basin hydrology has most probably been open due to the balance between sediment+water supply and subsidence rates. The increase in humidity may also have played a role in keeping the high groundwater table very near to the surface and thereby promoted the development of root channels and hydromorphism. The period of high fluvial channel activity (log Z3, Fig. 3) probably represents the final stages of the aggradation of the basin after deposition of the green/grey fine-grained sediments, resulting in development of an amastomosing fluvial system. However, the development of lake/pond bodies, especially those with sharp basal contact, could have resulted from subsidence pulses leading to the interception of the groundwater table with the surface. Freshwater lakes formed when the basin was in a complete balance, i.e. accommodation and sediment+water supply were in equilibrium. Brackish water bodies formed when subsidence rate gently surpassed the sediment+water supply resulting in relatively closed hydrological conditions.

7. Conclusions

1. The carbonate deposits of the Zarand basin in central Iran were deposited in an intra-continental siliciclastic–carbonate complex within four major depositional environments: shallow lacustrine environments; small carbonate lakes, ponds or marshes developed in floodplains of fluvial systems; carbonate-dominated and mixed carbonate–siliciclastic fluvial channels, and distal alluvial environments.
2. The Zarand basin carbonate deposits display many structures developed in palustrine settings including root traces, mottling, and development of calcareous nodules. They represent a unique sub-Recent analogue for ancient palustrine limestones.
3. Zarand basin is closely similar to a balanced-fill lake basin type in which the rate of sediment+water supply is in balance with the rate of the accommodation change. Sedimentological and palaeontological evidence indicates that the ancient wetland–lake system of Zarand evolved from fresh to brackish and again to fresh condition. Periods of fresh water conditions coincide with open hydrological conditions and periods of brackish water conditions correlate with the time spans when the rate of accommodation change gently outstripped the sediment+water supply.
4. The overall climatic regime of Zarand during the late Quaternary was semi-arid similar to the modern climate of the region. However, periods of stronger aridity and others with increased humidity can be distinguished. Palynological investigations in the future can help correlate climatic changes to changes in vertical facies successions to decipher the proportional role of tectonics and climate in the sedimentation of different stratigraphical units of the Zarand basin.
5. The drying out of the historical lake of Saveh was probably due to a combination of factors. Changes in basin hydrology can be attributed to increasing arid-

ity and discharge of groundwater through the activity of a fault system in the basin outlet. These natural phenomena were probably enhanced by anthropogenic factors in the form of groundwater withdrawal and land reclamation.

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